Geodetic monitoring of the Adroit landslide, Barcelonnette, French Southern Alps

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Abstract

Adroit is a district of the municipality of Barcelonnette in the French South Alps. This district is affected by a slow-moving landslide causing small displacements in the range of a few tenth of millimetre per year. This deformation pattern induces fissuring and toppling of most of the houses and some buildings have been evacuated or even destroyed. In order to document the deformation, the stakeholder in charge of risk management in the area (RTM-04 *Service - Restauration des Terrains en Montagne*), in coordination with University of Strasbourg and the municipality of Barcelonnette, has initiated several surveys, such as precise levelling, repeated GNSS benchmark acquisitions, borehole investigation (piezometers and inclinometers) and has conducted some geophysical investigation to understand the role of water circulation on the kinematics of the landslide. Further, some mitigation works such as surface water drainage have been carried out.
Seven geodetic benchmarks have been observed by GNSS techniques regularly (December 2014 September/October 2015, October 2016). Eleven levelling benchmarks has been installed and observed regularly (June 2015, September 2015, June 2016 and October 2016). Levelling observations are tied to the French Levelling Network (NGF) through two levelling benchmarks. These surveys reveal low vertical deformation rates of about 0.4-0.9 mm.yr^{-1}.
Moreover, a detailed description of the damages to the buildings has been carried out in order to document the most affected houses and follow the evolution of the damage in time. All these data are integrated in a georeferenced database for further investigation. The objective of this work is to present the monitoring strategy designed for this slow-moving landslide, document the accuracy of the used surveying techniques, and present maps of the deformation pattern.

Key words: landslide monitoring, GNSS, precise levelling; georeferenced database.

1 INTRODUCTION

Landslides are one of the most significant geohazards in terms of socio-economic costs, threatened infrastructures and human settlements. Monitoring their surface displacement is thus crucial for the prevention and forecast of landslides. In regions where large landslides (>$10^5 m^3$) cannot be stabilized and may accelerate suddenly, remote monitoring is often the only solution for surveying and/or early-warning. For small landslides, few monitoring are proposed except in urban areas (Figures 1 and 2).

The aim of the present study, focused on the Adroit landslide (e.g. a district in the municipality of Barcelonnette, Southern French Alps), has been to quantify and map the rates of surface deformation. To achieve these objectives, we used geophysical methods, such as borehole (piezometers and inclinometers) investigation and geodetic measurements (i.e. precise levelling and GNSS campaign).
Barcelonnette is located in the Ubaye Valley where several large landslides occured such as La Valette, Poche and Super-Sauze (Malet, 2003; Malet et al, 2016, Fig.1). These active landslides occur particularly in clay–shale deposits (Malet, 2003) which form unstable areas characterized either by movements along discrete shear planes (Hungr, et al, 2001) or by continuous deformation resulting from local factors such as steep slopes (N25°), weak mechanical properties of the ground, and presence of groundwater tables (Baum et al, 1998).

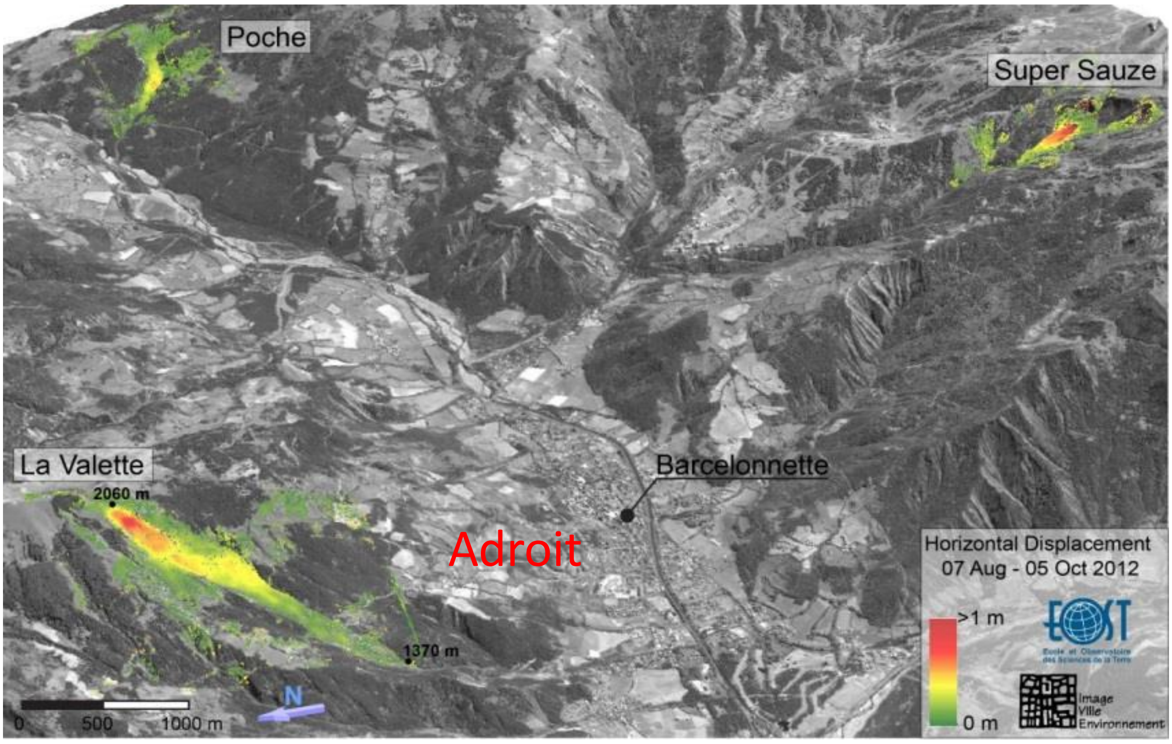

Fig. 1 Location of the Ubaye Valley (SE French Alps), and of the three main landslides affecting the valley (La Valette, Poche, Super-Sauze) and of the Adroit District in the municipality of Barcelonnette (Stumpf, et al 2012).

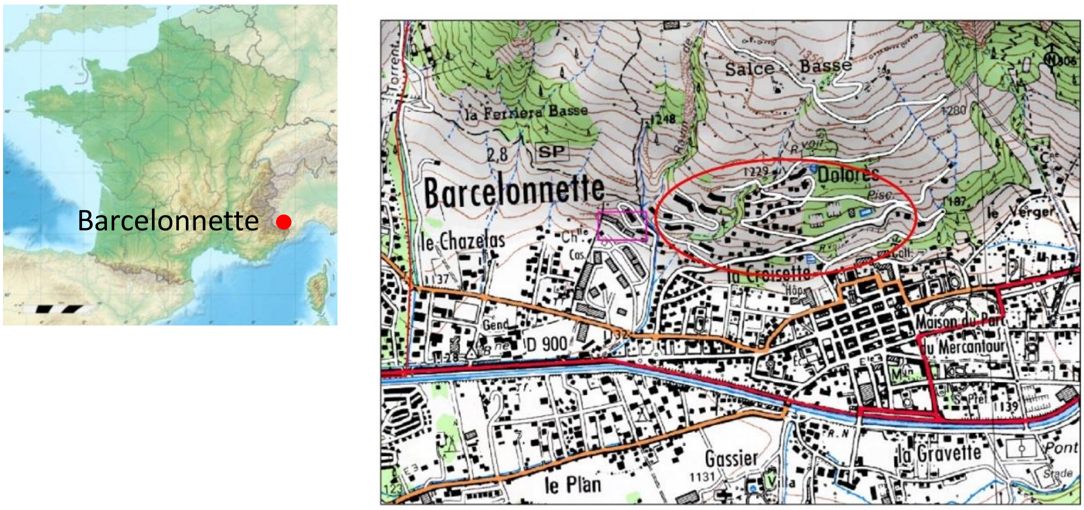

Fig. 2 Location of Adroit district in the municipality of Barcelonnette, SE French Alps.

2 THE ADROIT SLOPE

The Adroit district is located on the South-facing slope above the centre of Barcelonnette (Figure 2). The slope consists of a layer of poorly consolidated Quaternary deposits (e.g. moraine) which are superimposing a bedrock of Jurassic black marls (Figure 3). This lithological situation had led to the triggering of damages to roads and on many buildings (Figure 4). In some cases, some buildings had to be demolished (Figure 4). All the data on the buildings are integrated in a georeferenced GIS database for further investigation.

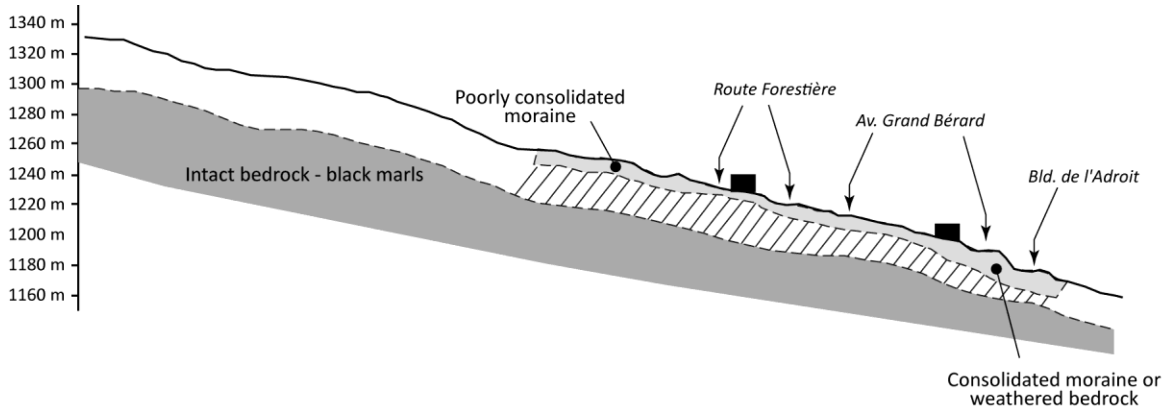

Fig. 3 Simplified geotechnical cross-section of the Adroit landslide with poorly consolidated moraine on top, consolidated moraine below and the bedrock of intact black marls (RTM-ONF, 2015).

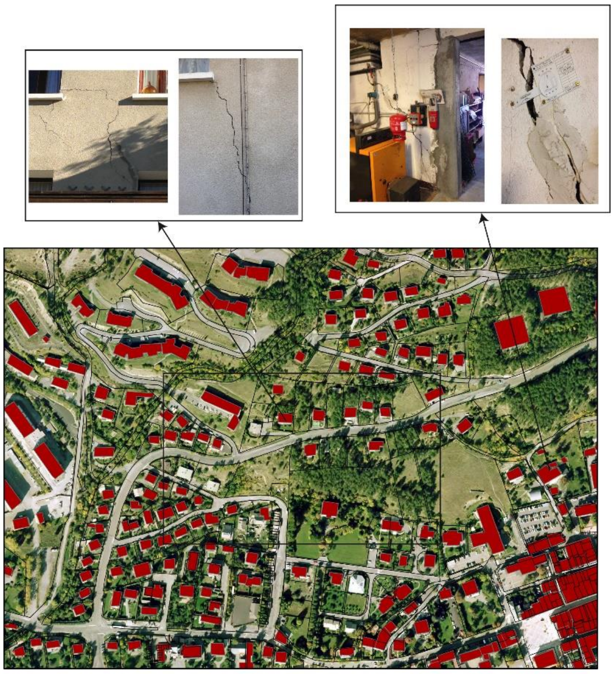

Fig. 4 Examples of cracks and deformations documented in the GIS georeferenced database.

3 GEODETIC MONITORING NETWORK AT ADROIT

In order to document the deformation, the stakeholder in charge of risk management in the area (RTM-04 *Service - Restauration des Terrains en Montagne*), in coordination with University of Strasbourg and the municipality of Barcelonnette, has initiated several surveys, such as precise levelling, repeated GNSS benchmark acquisitions, borehole (piezometers and inclinometers) surveys and has conducted some geophysical investigation to understand the role of water circulation on the kinematics of the landslide. Further, some mitigation works such as surface water drainage have been carried out.

3.1 ADROIT GNSS NETWORK

The investigated slope is about 800 m x 700 m. The permanent GNSS station of Barcelonnette (BACT) has been installed in December 2007 by Charted Surveyors in the Ubaye Valley (Figure 5). BACT is located on top of the hospital in the lower part and flat zone of the city (Figure 5). In December 2014, we have installed a second permanent GNSS station on the building of the Seolane Research Centre (Leica GR25 receiver and Leica AR10 antenna of SEOL, Figure 5). This antenna is outside the sliding zone and is used as a reference station. Moreover six concrete studs with steel have been built (red circles on Figure 5 denoted R1, R2, R3, R7, R8 and R11) and equipped with a geodetic benchmarks (BM) in December 2014. The 6 BM have been observed during 30 minutes up to 5 hours using GNSS Leica GR10 receivers and AR10 antennas in 3 campaigns in December 1st, 2014, September 29-30 and October 1st 2015, and finally in October 7th 2016. Most of the benchmarks BM are close to 10 piezometers of 30-40 m depth (not shown in Figure 5) and close to 9 inclinometers (not shown in Figure 5).

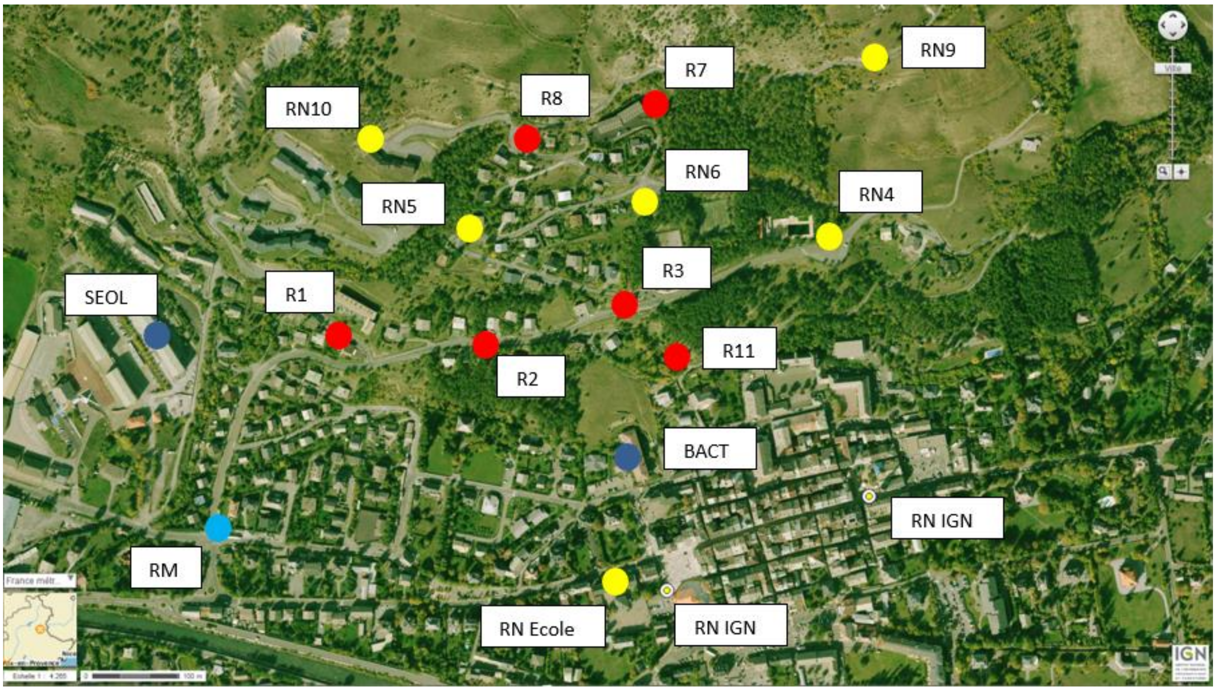

Fig. 5 Monitoring network equipped with levelling benchmarks (yellow circles), geodetic benchmarks (red circles) and two permanent GNSS stations (SEOL and BACT). Additional benchmarks (BM) has been installed in the lower flat area (RM).

3.2 ADROIT PRECISE LEVELLING NETWORK

The slope is equipped with several Levelling Benchmarks (LBM) of different origins. Two Levelling benchmarks (LBM) belong to the French Mapping Agency (IGN, *Institut Géographique National*) and are denoted RN IGN in Figure 5. 12 additional LBM were installed within the unstable slope (RN *Ecole*, RM, R1, R2, R3, RN4, RN5, RN6, R7, R8, RN9, RN10). The main levelling line runs from the RN IGN at Barcelonnette Hotel de Ville (RN IGN at the Southern part of Figure 5) to R8 and is about 2400 meter long (Figure 6). Four small levelling lines were established from RN IGN to R11, from RN IGN to RN IGN at Place Manuel (East part of the centre of the city, Figure 5), R3 to R4 and RN6 to R7. We observed four times the levelling network using digital level Leica DNA03 and invar rods in June 17-18, 2015 and using digital level Trimble DiNi 03 and invar rods in Sept. 29-30 and October 1st, 2015, June 16-17-18, 2016 and October 4-5, 2016. RN10 has been observed only once. RN9 has not yet been observed. Each section has been observed mostly in double run to check for observations, i.e. levelling is conducted twice, in opposite directions.

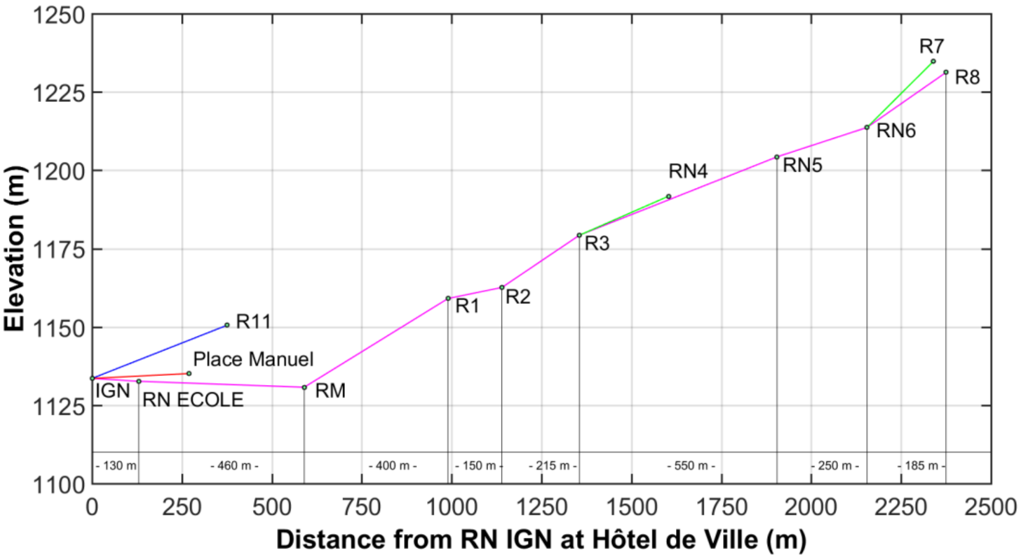

Fig. 6 Simplified profile of levelling lines of the Adroit network, IGN is the reference benchmark at Hotel de Ville. The colors indicate the established levelling lines.

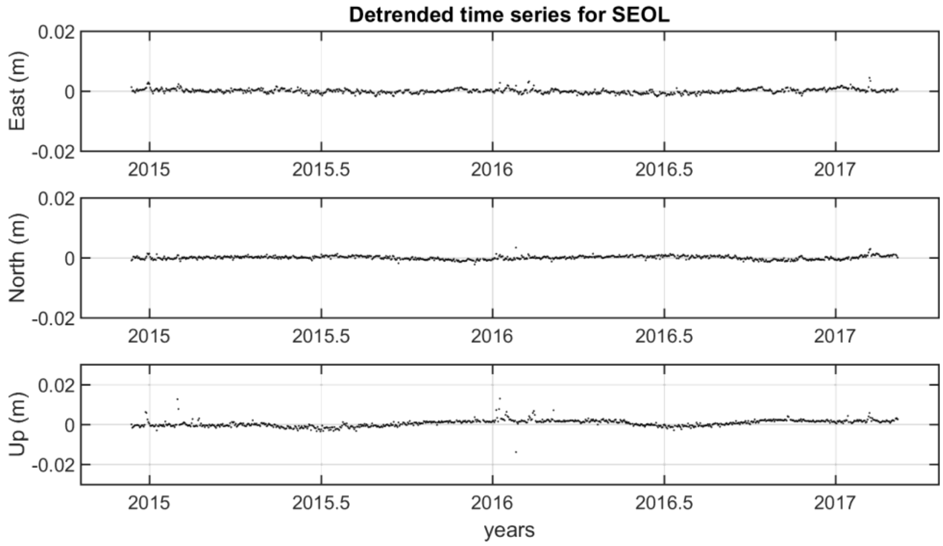

Fig. 7 Detrended time series of SEOL GNSS station positions for the period December 12, 2014 to March 7, 2017 (East, North and vertical components in m). Absolute tectonic plate motion is removed.

4 GNSS AND LEVELLING COMPARISONS

4.1 BACT-SEOL BASELINE

Using the version 5.0 of Bernese software, we computed the baseline BACT-SEOL for the period December 12, 2014 to March 7, 2017 using only GPS L1 observations because the baseline is small (about 600 m). Elevation difference of the BACT-SEOL baseline is of about 9 meters. Figure 7 shows the detrended time series of positions, i.e. absolute Eurasian tectonic plate motion is removed. Repeatabilities are 0.7 mm in east, 0.6 mm in north and 1.8 mm in vertical components for SEOL station. We supposed that the BACT station is stable. This leads us to conclude the stability of the SEOL antenna of better than 1-2 mm for this period of about 2.2 years (i.e. 805 days). We observed some noise in the vertical component in the winter season, this may be linked to snow accumulation on the radome of the GNSS antenna (Figure 7).

4.2 2014-2016 GNSS COMPARISONS

The GNSS observations of the BM were processed using the version 3.5 of the commercial Trimble TBC software. Comparisons of positions for the 3 periods (Dec. 2014, Sept/Oct. 2015 and June 2016) show no significant horizontal movement when considering a tolerance of 2.5 times the formal errors (Table 1). Estimated displacements in horizontal position vary from 3 to 14 mm for most points, except for R2 (38 mm for the period 2014-2015). Due to failure of equipment, R3 could not be measured in June 2016. Most sites are determined with a few mm accuracy except R3. This latter site is too close to high trees and exhibits multi-paths. R1 exhibits a high value (16 mm) because observation duration in 2014 is too short (4 min, due to battery failure).

Table 1. Annual horizontal and vertical discrepancies and associated formal errors for the GNSS positions of the 6 benchmarks during the 2 periods 2014-2015 and 2015-2016. The permanent GNSS station BACT is supposed stable for the period Dec. 2014 - June 2016.

	Horizontal (mm)	Horizontal (mm)	Vertical (mm)	Vertical (mm)
Benchmarks	2014-2015	2015-2016	2014-2015	2015-2016
BACT	0	0	0	0
R1	16 ± 7	6 ± 2	11 ± 5	2 ± 1
R2	38 ±15	6 ± 3	28 ± 8	-21 ± 3
R3	14 ± 6	Not observed	5 ± 4	Not obs. in 2016
R7	7 ± 2	5 ± 1	-2 ± 1	-7 ± 1
R8	4 ± 2	-3 ± 1	0 ± 1	-5 ± 1
R11	7 ± 3	4 ± 2	0 ± 2	-5 ± 1

4.3 2015-2016 PRECISE LEVELING COMPARISONS

By fixing the altitude of the LBM at Barcelonnette, we compute the altitudes of all the LBM for the 4 campaigns. Figure 8 shows vertical displacements for 12 LBM. Most of values are below 5 mm and are not significant, because periods of observations are short (4 to 8 months). Error bars on Figure 8 are about of 0.3 mm per station. Error increases as distance increases from the reference LBM of Hotel de Ville. (RN IGN). Most of the vertical variations are negative indicating a small subsidence of the slope.

If we intend to estimate a vertical rate for June 2015 to June 2016, we obtain three kinds of values. No motion or low motion for LBM i.e. below 0.04-0.4 mm.yr^{-1} (RM, R1, RN RN Ecole), sites with rates of 0.7 mm.yr^{-1} (R2, R3) and 0.8-0.9 mm/yr. R7 exhibits a high value but slope between R6 and R7 is steep and error accumulate in this section.

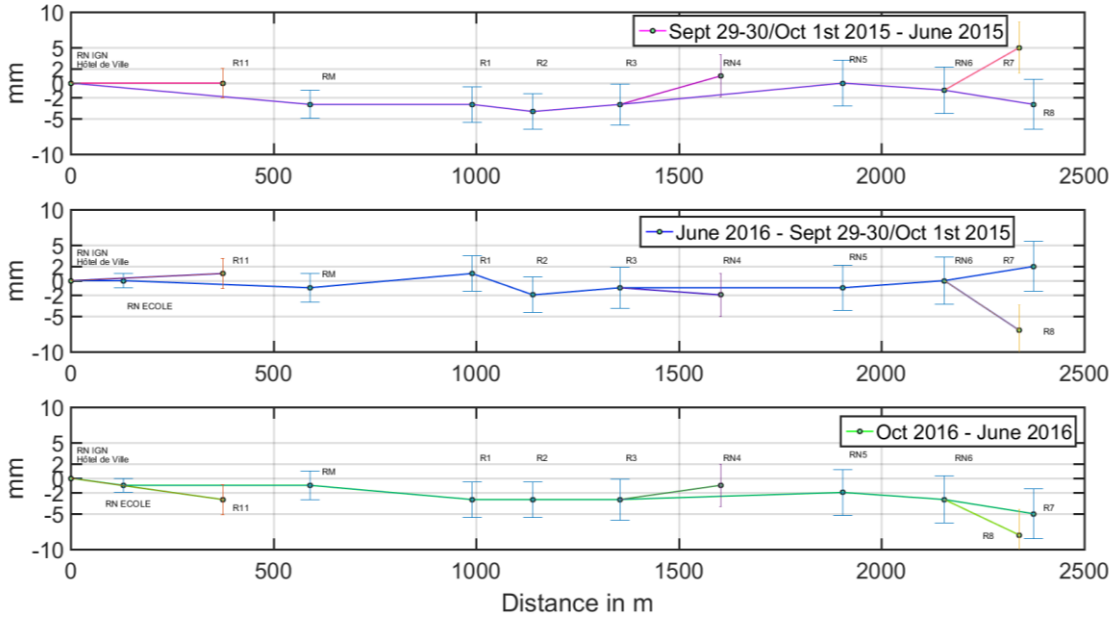

Fig. 8. Vertical displacements (mm) for 3 periods: June, Sept/Oct. 2015, June and Oct. 2016

5 CONCLUSION

In order to monitor surface deformation at the Adroit slope, a geodetic monitoring has been installed. GNSS and levelling campaigns for the period Dec 2014 to June 2016 reveal no significant horizontal motion, vertical displacements seems to show a low subsidence rate of 0.4-0.9 mm/yr. This monitoring will be continued in integrating geophysical measurements (inclinometers and piezometers).

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